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Indoor air quality improvement in natural ventilation using a fuzzy logic controller

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Abstract

The aim of the research was to design and validate the prototype of a device developed to improve the quality of indoor air by supporting the natural ventilation in building. A CO_2 sensor and thermo-hygrometer were used to measure the physical parameters of the indoor air. The developed device is based on the Raspberry Pi single-board-computer (SBC) and optical sensors. The prototype casing was made using 3D printing technology. The software was written using the Python 2.7 programming language. The key algorithm of control uses fuzzy logic. The effectiveness of the developed device has been confirmed. The use of the device enabled improvement of the indoor air quality. The presented device may be a solution to improve the indoor air quality by supporting the ventilation system.

Keywords: fuzzy logic, indoor air quality, natural ventilation

1. Introduction

Much research has shown that in buildings with natural ventilation systems, the indoor air quality is usually unsatisfactory or even unacceptable, possibly causing sick building syndrome (SBS). It has been also proven that poor indoor air quality affects people's work efficiency and causes feelings of discomfort (Strøm-Tejsen et al., 2016: 679–686; Gao, Wargocki, Wang, 2014; Wolkoff, 2013: 371–394; Taheri et al., 2016: 89–100). Indoor air quality can be described by the concentration of different contaminants (ASHRAE, 2011). Good air quality is what every building user expects (Polednik, 2013: 15–28; Fanger, Popiołek, Wargocki, 2003).

The main scope of the research was to design, build and validate a device that can efficiently support the natural ventilation process in occupied buildings. The role of the device was not only to measure the air parameters but also to assist the user in making appropriate decisions concerning the extent to which windows are opened in order to maintain the best indoor air quality with the minimum possible energy loses. Based on measured data and the calculation algorithm, the device suggests to the occupant one of five possible options relating to the extent to which the windows are opened. The suggested variant is the solution that should guarantee the optimum use of the natural ventilation system. Natural ventilation without heat recovery is responsible for 60% of the total energy losses in buildings (Recknagel, Sprenger, Schramek, 2008). An optimised air flow can reduce the inefficient operation of the system.

In the *ScienceDirect* database, which is in Elsevier – one of the world's largest editorial science offices 7,784 articles were published with the keyword 'indoor air'. In 2017 alone, 1,058 papers were published with the above keyword. The number of publications confirms the thesis that indoor air quality is a major concern worldwide.

Many residential and educational buildings are equipped only with inefficient natural ventilation systems. Research conducted in many schools show many cases of unsatisfactory air quality. Using ASHRAE standards (American Society of Heating, Refrigerating and Air-Conditioning Engineers), to obtain class 'A' indoor air, the ventilation rate should be around 10 dm^3/s per person with the minimum set on 3 dm^3/s per person (Fanger, 1999). The airflow is determined by the increased concentration of CO_2, the main source of which is human respiration. According to REHVA (Federation of European Heating, Ventilation and Air-conditioning Associations) (Andersson et al., 2006), the concentration of CO_2 in rooms should not exceed 1,500 ppm, but according to many standards of European and American countries, the value should not exceed the Peettenkofer's number (1,000 ppm). Many publications show (Toftum et al., 2015: 494–503; Canha et al., 2016: 350–365; Da Silva, 2012) that the acceptable level of CO_2 concentration is sometimes exceeded three times (3,000 ppm) (Bakó-Biró et al., 2012). Measurements in educational buildings show that the flowrate is insufficient to fulfil the standard requirements (Toftum et al., 2015: 494–503).

2. The quality of indoor air and its impact on human performance, well-being and health

The discussion on poor indoor air quality and its influence on comfort and learning ability is not new; however, we have recently been able to observe a significant increase in understanding interactions between different air parameters and their influence on humans (Fanger, Popiołek, Wargocki, 2003; Tham, 2016). During an experiment conducted in 1999 (Wargocki et al., 1999), the investigated group wrote 6.5% less text as a result of a decreased level of air quality. A good quality of air resulted in fewer mistakes increased well-being and fewer SBS complaints. Better air quality reduces absence due to sickness (Turanjanin et al., 2014: 290–296). Numerous investigations have shown the impact of indoor air quality on work efficiency and learning ability (Madureira et al., 2016: 198–205; De Giuli et al., 2012: 335–345; Wang et al., 2015: 288–296). Research (Wargocki et al., 2000: 222–236; Petersen, 2016: 366–379), showed an increase in efficiency in four out of eight tests in which the airflow was increased twice. A similar experiment was conducted by (Bakó-Biró et al., 2012), and demonstrated an airflow increase from 1.0 dm³/s to 8.0 dm³/s per person resulted in an increase in efficiency in four out of nine tests. Good learning efficiency is achieved with a certain level of factors affecting outcomes. Among these parameters are; concentration, short memorization and student's vigilance.

Research (Mendell et al., 2013: 515–528) has investigated the correlation between learning ability and airflow in 100 fifth-grade classes in the south western states of USA using normalised testing. The number of students passing the tests increased by 2.9% (maths tests) and 2.7% (reading tests) with the airflow increase by one dm³/s per person in the range of 0.9 dm³/s to 7.1 dm³/s per person.

Schools are an internal environment that are second only to the home with regard to the amount of time children spend in them. According to a report (OECD 2015), in European Union countries (EU21), primary school pupils (7–14 years old) spend an average of 776 hours per year at school, while junior high school students (15–18 years old) spend 895 hours at school. Children constitute a section of society that is more susceptible to air pollution; this is not only due to the incomplete development of their respiratory and immune systems but also from a relatively high ratio of inhaled air to bodyweight in comparison to adults. In addition, children's organisms are characterised by a weaker ability to cope with toxic substances. The quality of the internal environment of school classrooms should meet the highest standards due to the vulnerability of their users to its negative impact and exposure time. The fact that the efficiency of learning depends on the quality of the internal environment is undoubtedly an important issue for socio-economic reasons; however, a more important issue seems to be the impact of classroom conditions on student health.

Studies conducted in twenty-eight schools in California show that each increase in external air flow causes a decrease in absence due to illness by 1.6%. The authors of the study suggest that the costs incurred due to the absence of students far outweigh the savings obtained by limiting the energy used by the ventilation system (Mendell et al., 2013: 515–528). Similar results were also obtained in the case of attempts to assess the impact of ventilation and the prevailing room conditions for office workers. However, in the case of other research (Haverinen-Shaughnessy et al., 2015: 35–40), no statistical correlation was found between student absenteeism and parameters describing the quality of the internal environment. However, a significant correlation was observed between ventilation flow and the number of students who obtained satisfactory results from tests of maths and reading. The lack of a correlation between the internal environment parameters and the occurrence of health complaints among students was also obtained during research conducted in Finnish primary schools (Turunen et al., 2014: 733–739).

The results of the above-mentioned tests clearly prove that insufficient airflows have a negative effect on pupils.

3. Strategies to improve the quality of indoor air

Possible strategies to improve the quality of indoor air:
1) the replacement of a less efficient ventilation system, e.g. replacing a natural system for a more efficient alternative, such as a mechanical system;
2) the use of devices to improve the air quality (purifiers, humidifiers, air conditioners, ionizers, etc.);
3) the application of air-quality monitoring with feedback to the user;
4) use of appropriate pot plants in the room.

It should be borne in mind that these methods have different levels of efficiency. The first method is the most effective solution but is also the most expensive and is often difficult to implement. The second option is very local, so it cannot serve as a 'system'. The fourth solution, the use of appropriate pot plants, can only be considered as a complementary action.

A more convenient solution is to use the third of the aforementioned possible strategies to improve air quality – the use of air-quality monitoring with feedback. The solution will usually also require lower investment costs.

Bearing in mind the fact that humans are unable to determine the chemical composition of air by means of the senses, it is difficult for the user to assess when they should open the window in order to maintain adequate air quality. In addition, in the case of contaminated outside air, the opening of the windows can lead to the deterioration of the indoor air quality due to the inflow of pollutants from the outside. A solution that improves the indoor air quality and can be used in an existing building with natural ventilation is the installation of a continuous carbon dioxide monitoring system, which enables the user to react quickly to the deteriorating state of indoor air quality by adjusting the window opening.

This solution was successfully tested by Da Silva and Wargocki in an experiment conducted in a Danish school (Da Silva, 2012; Wargocki, Da Silva, 2015: 105–114). In their study, the impact of the above solution on air quality in a room in which a CO_2 meter with a light indicating the CO_2 concentration level was installed. The measurements were performed in two identical primary school classrooms during lessons over two-week periods during the heating and summer seasons. On average, there were around twenty-four students in each class who, together with the teacher, had the option of opening five windows. The use of the meter with feedback enabled maintaining the CO_2 concentration level below 1,100 ppm during the experiment. In the absence of the meter, the concentration value was around twice as high. Opening windows did not significantly affect the room air temperature and students did not complain about drafts or cold sensation. The external temperature of the air was in the range of 6–12^{o}C.

Similar research to the Danish study was conducted in the Netherlands, where the subject of investigation was the effect of an excessive-CO_2-concentration warning device on users' window-opening choices for improving natural ventilation and indoor air quality (Geelen et al., 2008: 416–424). Measurements performed in twenty classrooms classes during the heating period were divided into three measuring cycles: before the device was used, during its use and after application. In addition to receiving instruction on operating the device In addition to the device, users and teachers were instructed about how to properly maintain good air quality. As a result of the above solution, a reduction in the number of exceedances of carbon dioxide above 1,000 ppm to a level of 38% of the duration of the measurement period was obtained, compared to the period before the implementation, in which the value was 64%. The use of a carbon dioxide sensor with the appropriate instructions on how to open the window depending on the CO_2 concentration significantly improved the air quality in the tested room. In ventilation technology, carbon dioxide is used as an indicator of air quality. Increases in the concentration of this gas in the room are strongly correlated with the presence of people in this room. It should be remembered that people are not the only source of air pollution in buildings; building materials and equipment in rooms can emit, among other contaminants, volatile organic compounds (VOCs). These compounds have a significant impact on the level of indoor air quality. Their prevalence, volatile properties and general pathogenicity make them dangerous to human health (Zabiegała, 2009: 303–315). It should be borne in mind that impurities in the internal air are usually not present in high concentrations; however, due to their long exposure to humans, they have an impact on health and well-being. Both in the case of air pollution from people and that which is emitted by the building, the solution for improving air quality is to remove contaminants by extracting them from the room and diluting them by supplying fresh air. Therefore, ensuring the proper efficiency of the ventilation system is a key issue for obtaining adequate indoor air quality.

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4. Methods

The main goal of the research was to try to solve the problem of low quality indoor air in rooms with natural ventilation. In order to identify the problem, the authors conducted measurements of the physical parameters of the air (temperature, relative humidity, CO_2 concentration) and the subjective assessment of the microclimate of the room with natural ventilation. The authors have not found any consumer electronic device for monitoring air quality using a similar algorithm based both on the level of carbon dioxide concentration and its fluctuations. The use of this solution is common in control processes in both ventilation and air conditioning as well as in other fields that use process control.

5. Construction of a device to improve the indoor air quality

In the solution presented in the paper, the authors propose visualising the level of air quality (by means of coloured lights) in order to make the user aware of the current state of air quality in the room. The user, being aware of the problem of low air quality, may take actions to change this state. In contrast to popular devices available on the market, the proposed solution will show the user how to improve the air quality. The proposed solution is calculated depending on the current CO_2 concentration and its change over the preceding five minutes. Both input variables are then processed by a control algorithm, using premisses containing instructions on the proper way to ventilate the room. Control systems which use expert knowledge in a controlled process are known as knowledge--based systems. Control systems in which the knowledge of an expert on a controlled process is known as 'knowledge-based systems'.

Knowledge-based systems (KBS) are closed-loop control systems that introduce knowledge that cannot be introduced using analytical models or other logical mechanisms. It can perform a closed loop operation directly, replacing a conventional control algorithm. The introduction of knowledge describing the regulated process is possible by using fuzzy logic. Fuzzy control can be considered as a special, knowledge-based (real-time) system that implements the knowledge of a person who is an expert in a regulated process (Driankov, 1996). The knowledge expressed by the expert determines the dependencies of the input / output of the control mode, in the form of the 'situation–action' rules, called the if-then condition. The purpose of the FKBC (fuzzy knowledge-based controller) is to remove significant process output errors (inadequate window--opening situations) by appropriate tuning of the control variable (information on the extent in which windows are opened).

The FKBC controller consists of three basic blocks:

- block of fuzzification, the task of which is to determine the degrees of the belonging of input values occurring in the form of sharp values to fuzzy sets;
- block of inference, the task of which is to define shadowy regulatory decisions based on the degrees of membership of input signals and the adopted control rules base (premisses);
- defuzzification, the task of which is to sharpen regulatory decisions to a standardised field on the basis of specific degrees of belonging.

The fuzzy controller can be used to help adjust the degree to which building users open windows and be treated as an auxiliary system, providing support for users in making decisions. The use of a fuzzy controller in a single closed loop, by using a base of rules (premisses) enabling the obtaining of an output signal (in this case information supporting the manual adjustment of the window) without the need for complicated mathematical descriptions of the process (Kulis, Bogacki, 2016).

Implementation of this type of system in a room with natural ventilation enables users to properly control the degree of window opening in order to obtain satisfactory air quality by obtaining the proper efficiency of the natural ventilation system.

The purpose of the device is to obtain satisfactory air quality in the room while maintaining the remaining parameters of the microclimate (thermal comfort) and of energy efficiency at acceptable levels. In contrast to commercially available air-quality monitoring devices, the developed device, in addition to reporting air--pollution levels, communicates with the user informing them of what exactly they should do to improve the air quality in the room in which they are currently residing. In the case of rooms equipped with a natural ventilation system, the ability to change ventilation efficiency is limited to only the adjustment of windows. The device suggests to the user in real time the extent to which they should open the window, informing them about it through the information displayed on the device screen and the mobile application. In addition, it draws the user's attention to the need to change the window adjustment by means of lights (flashing housing element) and a sound signal. The device is not equipped with an additional module or external device that would allow checking the current degree of window opening, which may cause misleading indications when the device is used in some situations.

In the case of increased concentrations of external air pollutants, opening windows is not recommended due to the possible inflow of contaminants into the room. Despite the commonly available data on the condition of the outside air, the user is not always aware of the current hazard resulting from the increased concentrations of pollutants in the outdoor air. The device has been programmed in such a way that enables reading data from the air-quality monitoring system which is operated by the Airly company. The data is read from the nearest sensor measuring the concentration of suspended dust. This information is then processed by a control algorithm, which in the case of exceeding the permissible level of PM2.5 suspended particulate matter in the outside air informs the user by displaying a message on the screen of the device. The device also informs the user about the need to open the window only with the acceptable concentrations of dust suspended outside.

Simple information about when to open / close the window allows the user to easily take care of the air quality of the room in which they are currently staying. In addition, it raises the user's awareness of the state of air quality and teaches them how to develop appropriate actions and reactions to its condition. The solution is a much cheaper and easier implemented way to improve room air quality than the replacement of the ventilation system. In addition, the device is small, so the user is able to take care of clean air literally everywhere, taking the device with them and mounting it in the room in which they are currently staying.

6. Construction elements

The design of the application device using the fuzzy logic algorithm was based on the popular Raspberry Pi single-board-computer in the Zero W version. The Raspberry PI (Fig. 1) supports the Debian system based on the GNU / LINUX operating system.

The device uses temperature, humidity, carbon dioxide and suspended dust sensors to identify air parameters. To measure the temperature and relative humidity, the DHT 22 sensor commonly used in ventilation systems was used (Fig. 2a). Sensor measuring range: relative humidity 0–100% RH, temperature -40 to +80°C. The accuracy of the measurement of relative humidity is ±2% RH, and for temperature it is ±0.5°C.

The MH-Z19 carbon-monoxide sensor (Fig. 2b) measures the concentration value in the range of 0–5,000 ppm for relative humidity <95% RH (measurement accuracy: ±50 ppm). The MH-Z19 sensor uses a non-dispersive infrared absorption (NDIR) method to measure the CO_2 concentration.

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Fig. 1. Single-board-computer Raspberry PI Zero W (source: Raspberry Pi Zero W (Wireless) Australia (core-electronics.com.au))

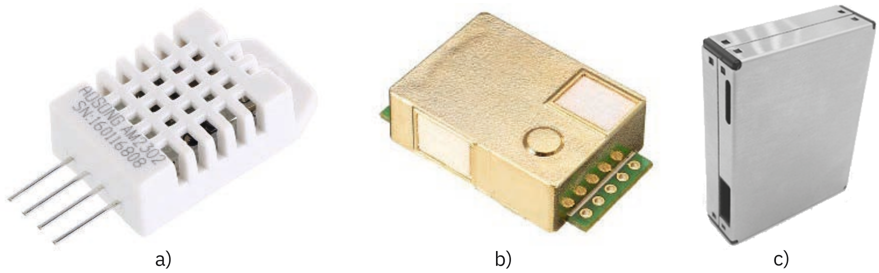

Fig. 2. a) Type DHT22 temperature and relative humidity sensor, b) Type MH-Z19 CO_2 sensor, c) Plantower PMS7003 suspended particulate matter sensor (source: readme.io; greatrctoys.com; aqicn.org)

Fig. 3. The prototype of the device (author's work)

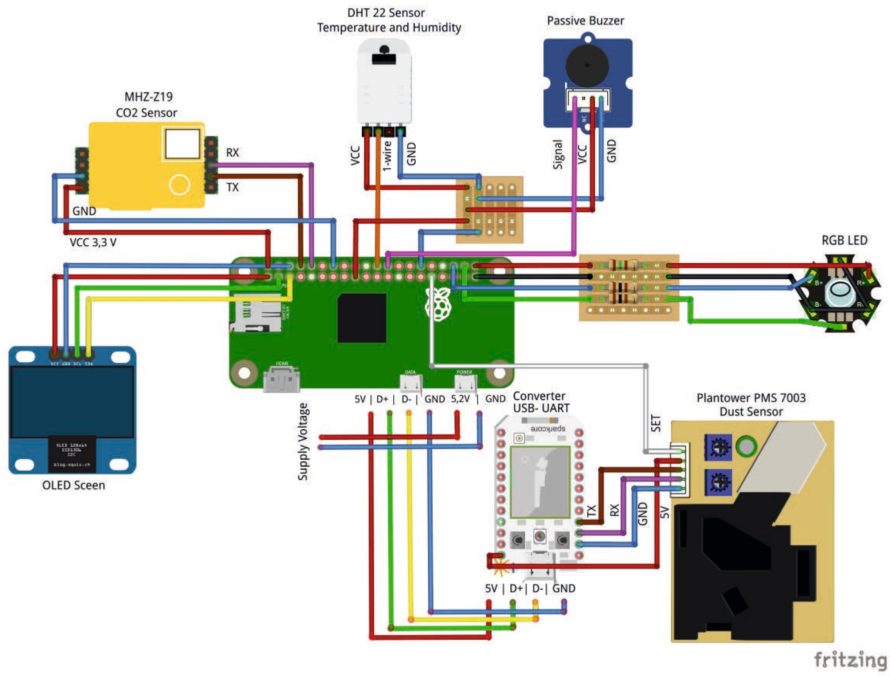

Fig. 4. Electrical scheme of the device to improve indoor air quality (author's work)

The Plantower PMS7003 suspended particulate matter sensor (Fig. 2c) performs measurements under operating conditions: temperature -10 to +60°C, relative humidity 0–99% with a measuring range of 0–500 μg/m³ (PM2.5) and a measurement accuracy of ±10%.

In order to visualise the result of the control algorithm, the device was equipped with a display working with OLED technology with the SH1106 controller. The display is used to present information in the form of text, i.e. the data of measured parameters in real time and the result of operation (the suggested extent of window opening).

The MH-Z19 and PMS 7003 sensors communicate with the SBC via the universal asynchronous transmitter-receiver UART interface. This is an integrated circuit for the asynchronous transmission and reception of information through the serial port (Wikipedia). Due to GPIO (general-purpose input / output) access to only one of the UART interfaces available in the SBC, it was necessary to use a USB-UART converter, which enabled both sensors to be connected at the same time. The DHT22 temperature and humidity sensor has a digital interface. The connection diagram of the device with individual modules is shown in Fig. 4.

7. Software

The source code of the device was created using the Python 2.7 programming language. Each of the used sensors is supported by a program that writes the data to a file. The main source code reads the appropriate number of records, which are then averaged and used in further code instructions. Readings of CO_2 concentration and its error in time are used in the algorithm responsible for fuzzy regulation. The average values from the sensors are displayed on the screen of the device to enable the user to monitor all air-quality parameters. In addition, the device downloads data via Internet connection from Airly's air-quality monitoring system that provides free access to your data. Information on the concentration of dust suspended in the outside air is used to alert the room user about the risk of inflow of pollutants from the outside in the case of an open window. A logic diagram of the device operation is shown in Fig. 5. Programs that support sensors and the main program are started automatically at system startup. In addition, at system startup, a program checking the operation of executive programs is started. In the event of an error in one of the programs (which causes the program to close), the checking program will restart the executive program, thus keeping the device running continuously.

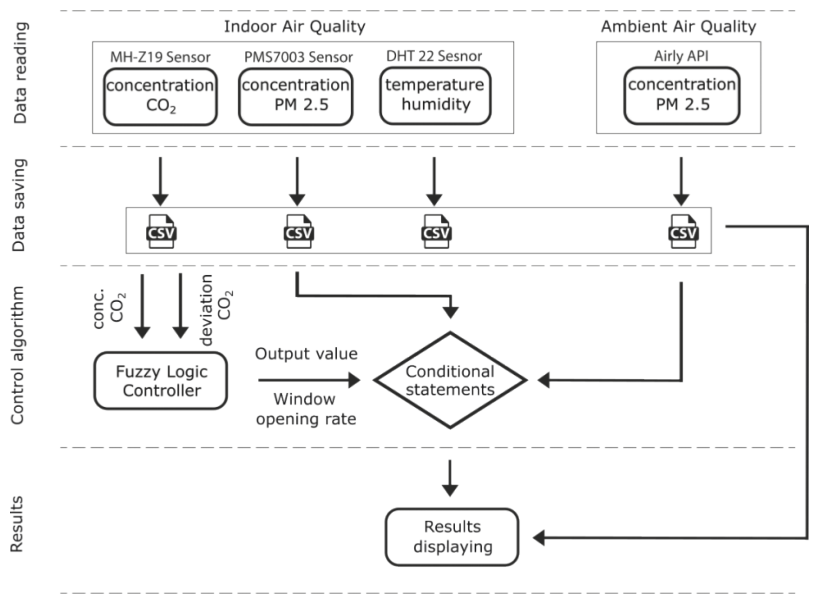

Fig. 5. Logic diagram of the operation of the device to improve indoor air quality (author's work)

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8. Fuzzy logic controller

Fuzzy logic controllers use fuzzy logic that was created by L.A. Zadeh as a consequence of the creation of fuzzy sets in 1965. The use of flogic in regulators results from the possibility of using the acquired knowledge about the regulated process in order to properly tune the regulator, i.e. setting its control parameters. In contrast to the classic methods of selecting the settings of conventional controllers, tuning the fuzzy controller does not require knowledge of the mathematical description of the dynamics of the regulated process (Brzózka, 2004). The fuzzy logic controller algorithm was implemented using the scikit-fuzzy library, which is available as open source. The algorithm is based on the knowledge base represented by IF-THEN rules and membership functions. The input quantities are the CO_2 concentration in real time and the error, i.e. the change in CO_2 concentration over a period of five minutes. The resulting output value is the window opening rate expressed as a percentage (range 0–100%). Input data as the so-called 'crisp' are converted to fuzzy values in the fuzzification process. The fuzzy values are used in the inference block that makes decisions for what action to take based on a set of 'rules' consisting of 'IF-THEN' premisses. The structure of the inference block is based on a model knows as the Mandami model. The results of all the rules that have fired are 'defuzzified' to a crisp value by 'centroid' (centre of gravity) methods. The scheme of the algorithm is shown in Fig. 6.

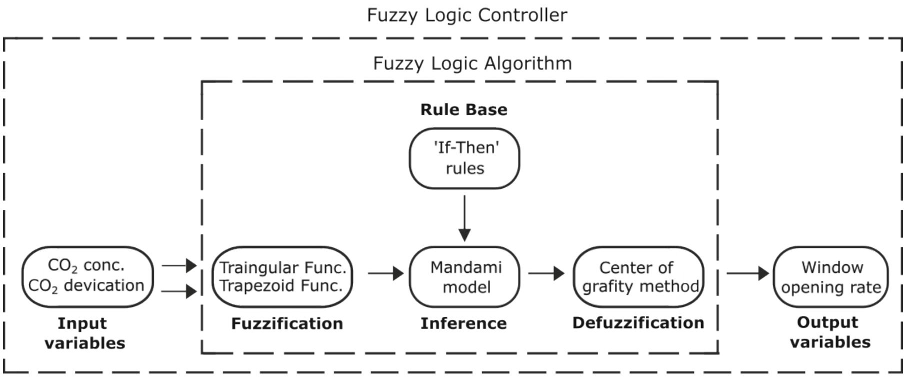

Fig. 6. Diagram of operation of individual blocks of the fuzzy controller (author's work)

The fuzzification of input variables coming from sensors consists of their transformation into fuzzy sets based on specific affiliation functions. The functions of the carbon dioxide concentration and its change over time have been determined in such a way that takes into account the categories of air quality. The function was optimised based on the evaluation of the effects of the device during prototyping. Affinity functions allow the ranges of fuzzy input values to be specified to assign individual linguistic variables to them. Below is an example of a declaration of variables in the device's source code for carbon dioxide concentration.

co2_equal_good = co2['good'] = fuzz.trapmf(co2.universe, [300,300,800,1200])

The lower limit of the function range is 300 ppm due to protection against the occurrence of values below the declared value, which would cause an error in the calculation of the algorithm. The value of carbon dioxide concentration in the external air was assumed at the level of 400 ppm (the most common value), hence the fact that the declared lower limit avoids calculation error.

Membership functions have been declared as 'triangular' functions (fuzz.trimf) and 'trapezoid' functions (fuzz.trapmf). The linguistic variables are defined as 'good', 'OK', 'poor', 'unhealthy', they are contractual names accepted by the authors in order to apply linguistic variables in the next steps of the algorithm. The membership functions for the carbon dioxide concentration level are shown in Fig. 7.

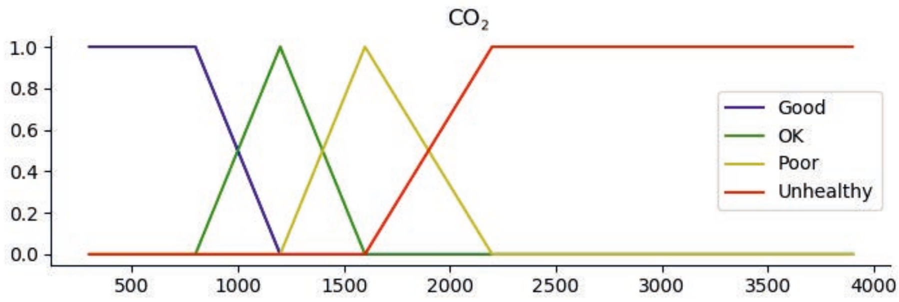

Fig. 7. Functions of belonging to sets of fuzzy carbon dioxide concentration values (author's work)

The second input variable of the fuzzy logic algorithm is the error in the concentration of carbon dioxide, i.e. the change in its concentration over time. Due to the dynamism of changes in CO_2 concentration in cases in which its source is people staying in the room, a short error time of five minutes was adopted. This solution allows the device to quickly adapt to the current factors affecting the CO_2 concentration in the room. An important factor affecting the quality of indoor air is the change in the efficiency of natural ventilation, which is dependent on changes in atmospheric conditions and the extent of opening windows in the room. Another factor affecting the quality of air are people, who are also the main source of air pollution contaminates in the room, including carbon dioxide.

The human body produces carbon dioxide in the process of breathing, which in the device being built serves as an indicator of indoor air quality. Reading both the actual concentration of carbon dioxide and its change makes it possible to estimate the conditions that will occur in the room. This solution allows the user to provide guidance on the required degree of window opening, taking into account the expected change in air quality, enabling them to react early.

Membership functions for a variable representing a change in carbon dioxide concentration over time are declared in a way that allows three categories of changes to be distinguished – positive, negative and permanent (no changes). The 'positive' category has been declared as two membership functions. Linguistic variables are defined as: 'negative' - for negative values, 'constant' – for values ranging from -100 ppm to 100 ppm representing a constant concentration level, 'positive' and 'very positive' for positive values. The ranges were adopted on the basis of our own observations on the variability of carbon dioxide concentration in a room with variable user load. The functions of belonging with regard to changes in carbon dioxide concentration used in the fuzzy logic algorithm are presented in Fig. 8.

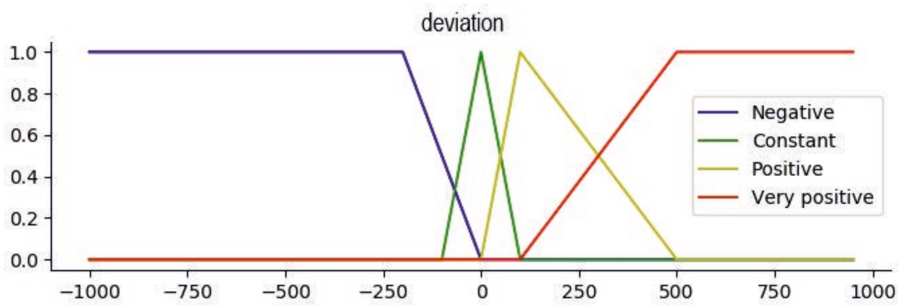

Fig. 8. Functions of belonging to sets of fuzzy values of carbon dioxide deviation (author's work)

The control process is based mainly on the inference block, the task of which is to accept input variables from the fusion block and provide output values to the defuzzification module according to specific rules in the 'knowledge base'. In order to represent the knowledge allowing proper adjustment of natural ventilation to the current conditions in the room, so-called premises or IF-THEN instructions are used. The rules database contains causal relationships between the fuzzy sets of inputs and outputs. The general form of the premisses is presented below:

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IF CO_2 is <function of belonging> and/or DEVIATION CO_2 is < function of belonging > then RESULT is < function of belonging >.

The applied model of fuzzy inference rules is a set of MISO system rules – multiple input single output using the Mamdani minmax method (Mamdani 1977). The premisses consist of two simple premisses combined with a logic and rendering representing the product of fuzzy sets, i.e. the minimum operation (f_{MIN}).

$$\mu_C(y) = \min[\, \mu_A(x_1), \mu_B(x_2)]$$

where:
$\mu_C(y)$ – output fuzzy set
$\mu_A(x_1), \mu_B(x_2)$ – input fuzzy sets.

In the case of using the Mamdani model, the output set is determined by the declared function of assigning belonging the conclusions $\mu_C(y)$ to the given fuzzy set.

The membership function ranges represent the degree of window opening in per cent. In order to enable the intuitive use of fuzzy sets in the interference block, as many as seven function intervals representing the possibility of adjusting the window were assumed. The functions of assigning to sets of fuzzy values of the conclusion – the extent of window opening is shown in Fig. 9.

The next stage of operation of the inference block is the aggregation of conclusions (i.e. fuzzy sets) by adding them according to S-norms. Used in the Mamdani model, it uses the maximum operation (f_{MAX}).

$$\mu Output_i(x) = \max[\, \mu_{C1}(x), \mu_{C2}(x), \ldots, \mu_{Ci}(x)]$$

where:
$\mu Output_i(x)$ – result fuzzy aggregate set,
$\mu_{Ci}(x)$ – output fuzzy sets.

The last stage of operation of the fuzzy logic model is the defuzzification process of the resulting fuzzy set. For this purpose, the centre of gravity method (centroid) was used, the advantage of which is to include all active rules. The effect of the defuzzification block is the centre of gravity of the figure being limited by the chart of membership functions and the axis.

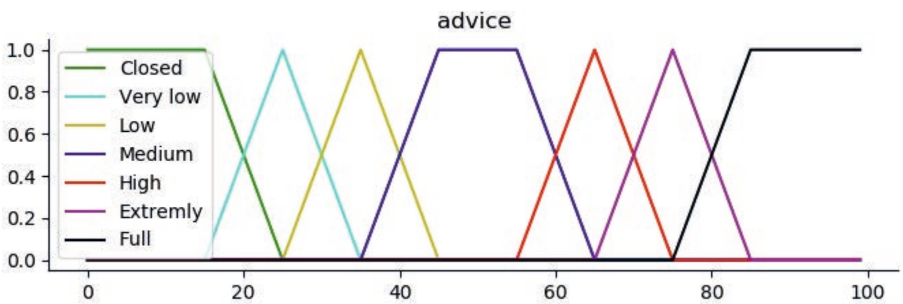

Fig. 9. The functions of assigning to sets of fuzzy values of the conclusion – the extent of window opening (author's work)

In order to present the operation of the fuzzy logic model in a three-dimensional graph (Fig. 10), a 'control surface' representing the output results of the regulator is presented. For each pair of acute inputs from the whole range of declared membership functions, the crisp output value was calculated.

The main algorithm of the device uses the final result of the fuzzy logic algorithm, classifying it into defined window-opening ranges to further process and check the declared conditions.

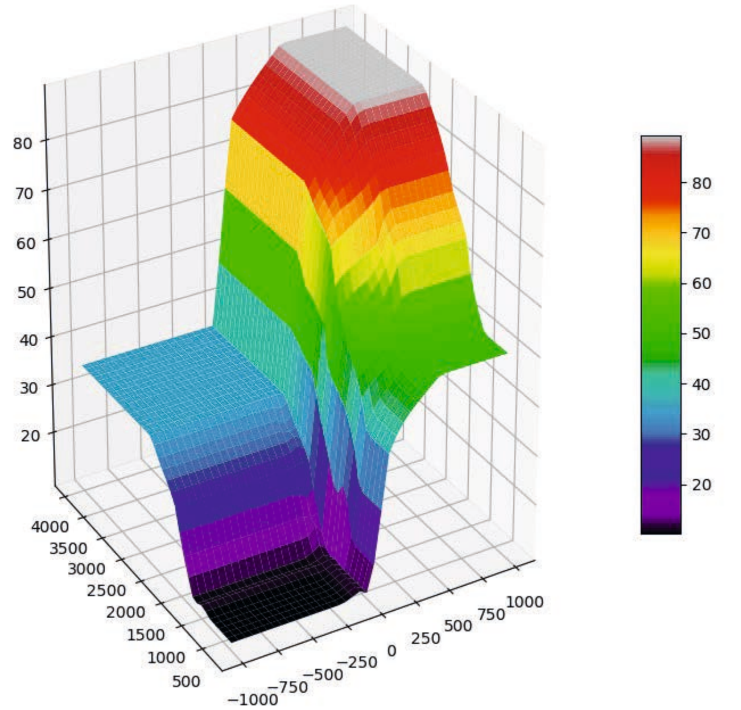

Fig. 10. Three-dimensional plot – control surface, X-axis – CO_2 offset [ppm], Y-axis – CO_2 concentration [ppm], Z-axis – conclusion – window opening degree [%] (author's work)

9. Conditional instructions

The conditional expressions make it possible to perform various calculations depending on the logical value of the defined expression (instruction). The ability to conditionally decide on the next step made enables the implementation of many alternative blocks of code. The most popular type is the If-Then expression (Wikipedia, 2018).

The use of conditional instructions in the main code of the device program enabled execution of specific blocks of code depending on the fulfilment of defined conditions regarding the measured quantities. Depending on the conditions, the program implemented the appropriate blocks of code to obtain the final result in the form of information for the user. The general scheme for executing conditional instructions by the program is shown in Fig. 11.

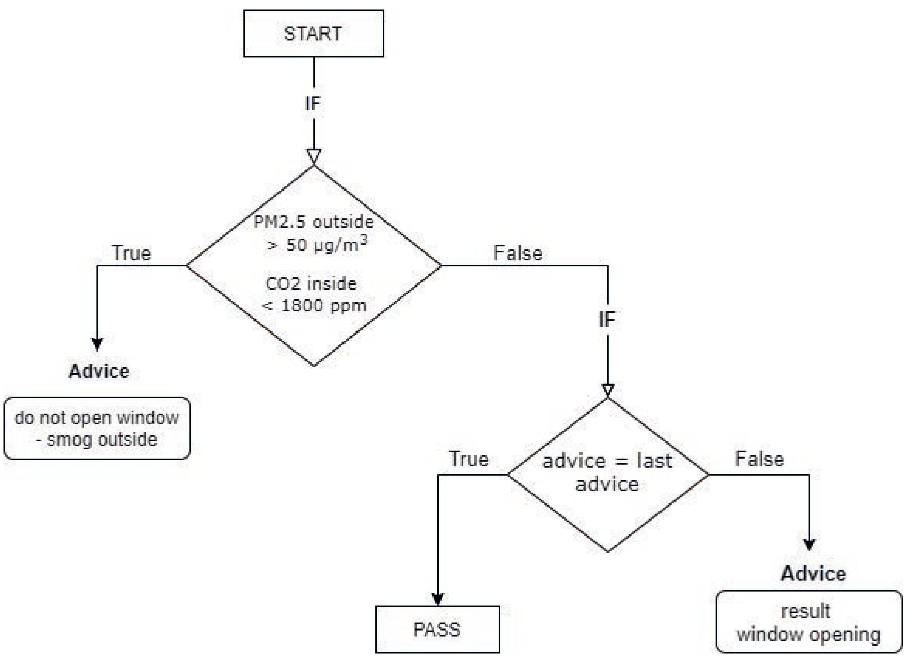

Fig. 11. A general scheme of conditional instructions for the device program (author's work)

https://doi.org/10.37705/TechTrans/e2020045

10. Communication with the mobile application

In order to follow the current results of air quality measurements and the result of the algorithm, the device has been connected with a mobile application designed for the Android operating system. The communication was implemented using the ThingSpeak platform, which enables the collection and archiving of data from sensors and then using it to develop IoT (Internet of Things) applications. The use of the application enables the results of device measurements to be tracked in real time. In addition, the application enables the generation of averaged charts from the data of measurement periods of all measured quantities. It also provides the final result of the device's control algorithm, i.e. the suggested extent of opening the window. Tracking the result of measurements and the result of operation of the device through the application allows the user to react to the current state of air without the need to track the device itself. The solution can be used in rooms where people responsible for ventilating a room are occupied with other activities, such as the case with teachers.

11. Evaluation of the effectiveness of the developed device

In order to check the results of using the device under real conditions, measurements were taken in a room with an area of around 10 m^2 located in a block of flats built in 2000. During the measurements there was one person in the room. The device test was divided into two parts. In the first part, the room window was closed for the entire duration of the measurements, which was 24 hours (from 06:00 on 20/09/18 to 06:00 on the next day). From around 07:00 to around 18:00, the user was not in the room. During this time period, the concentration of carbon dioxide remained at a level close to the concentration of this gas in the external air, around 400 ppm. During the hours the user was in the room, the concentration increased significantly, reaching the highest level of approx. 2,200 ppm. Attention should be paid to the variability of the trend (from about 18:00 to 6:00 the next day) describing the change in carbon dioxide concentration over time. The change in CO_2 concentration as a function of time is initially dynamic, then the increase in CO_2 concentration proceeds slower, leading to maintaining an approximately constant level of CO_2 concentration of around 2,100 ppm.

$$\dot{V} = \frac{\dot{E}}{C_{pom} - C_{naw}}$$

where:
$\dot{V}$ – ventilation airflow, m^3/h,
$\dot{E}$ – emission of a given pollutant into the room, ml/h,
C_{pom} – concentration of a given pollutant in the indoor air, ml/m^3,
C_{naw} – concentration of a given pollutant in the supply air (outside), ml/m^3.

From the above relationship, which was maintained during the measurements, the formula assumes an average outside CO_2 concentration of 400 ppm, and a maximum CO_2 concentration in the room of 2,100 ppm. The average emission of carbon dioxide at a 24°C is 12 dm^3/h (Rozporządzenie Ministra Infrastruktury, 2004).

The average value of the ventilation air stream at the above assumptions is about 7 m^3/h, which is more than 4 times lower than required by the (Rozporządzenie Ministra Infrastruktury, 2004), i.e. 30 m^3/h in the case of rooms separated from the rooms where there are ventilation openings (WC, kitchen) at least two doors. Fig also shows the CO_2 concentration error, i.e. a change in time of 5 consecutive minutes. Due to the short period of time (5 min), the error values are usually around several dozen ppm/5 min. The degree of window opening suggested by the device is shown in a bar graph, broken down into

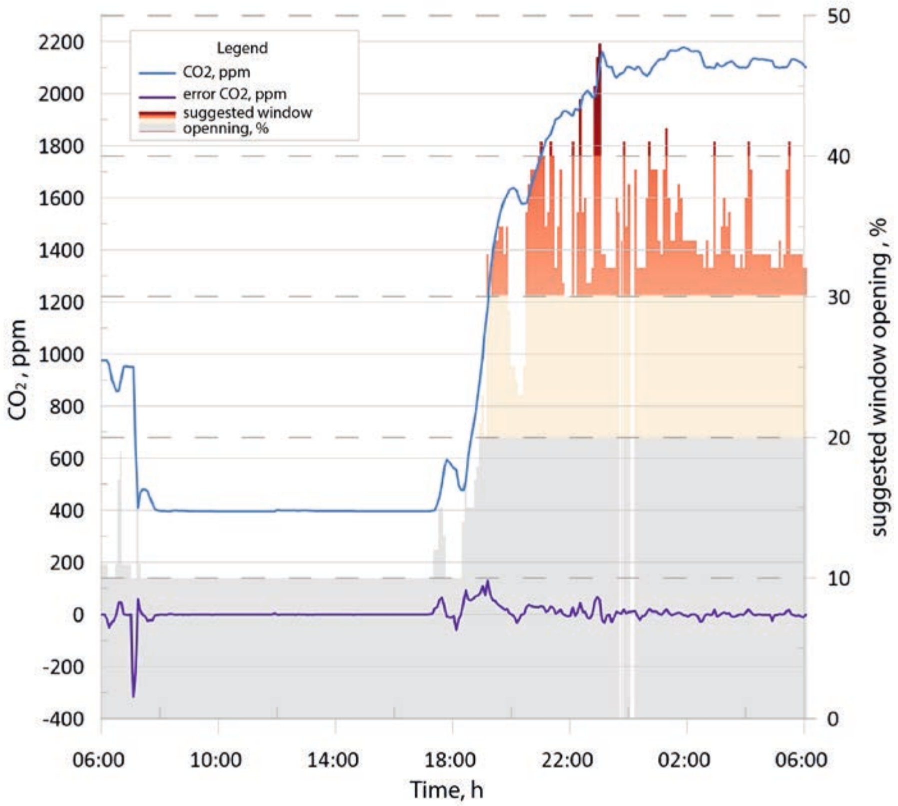

Fig. 12. Device test – change of concentration, CO_2 deviation and suggested window opening in 24 hours, unregulated window (author's work)

colors indicating the extent the window is opened (light gray – closed window, and another 'microluft', 'luft', slight opening).

The second part of the test consisted in using the methods of opening the window suggested by the device during the measurements. As in the first part, the test lasted 24 hours from 06:00 on 23/09 to 06:00 on 24/09. In contrast to the first part, the user was in the room throughout the measurement period, except for a few shorter periods in which he left the room. In addition, during the test there was a change in the load of the room, i.e. in a short period of time there were simultaneously three people in it. It was observed that as a result of using the device, the level of carbon dioxide reached a concentration level of around 1,200 ppm (Fig. 12). In comparison with the maximum value obtained in the first part of the test, it is lower by about 900 ppm. Assuming that a steady state occurred in the room, during which the average CO_2 concentration was 1,200 ppm, it is possible (using the formula used in this chapter) to calculate the approximate average air flow rate (assuming emission and concentration of supply air as before). In the second part of the test, the average ventilation air flow was 15 m^3/h. During the measurements, the user did not feel drafts or cold while the window was unsealed. One-time opening of the window (50% opening of the window around 22:30) caused discomfort due to the feeling of coolness of the outside air. On this day, the outside air temperature during the day was around 9°C, during the night it decreased to 6°C. There was no significant change in room temperature (>1.5°C) caused by unsealing / opening the window. After about 11:00 PM, the window was left in the 'microluft' position, which made it possible to maintain a low CO_2 concentration during the user's sleep.

The use of the device in the room made it possible to increase the efficiency of the ventilation system and improve the air quality. As a result of the device's suggestions regarding the time and the extent of window opening, an average CO_2 concentration level of 1,200 ppm was obtained. The test confirmed the functionality and effectiveness of the proposed solution for improving indoor air quality in rooms with natural ventilation. It should be noted that the maintained level of CO_2 in the room is higher than the recommended level of Petenkofer's number – 1,000 ppm. The device requires verification of the control algorithm in terms of defined

https://doi.org/10.37705/TechTrans/e2020045

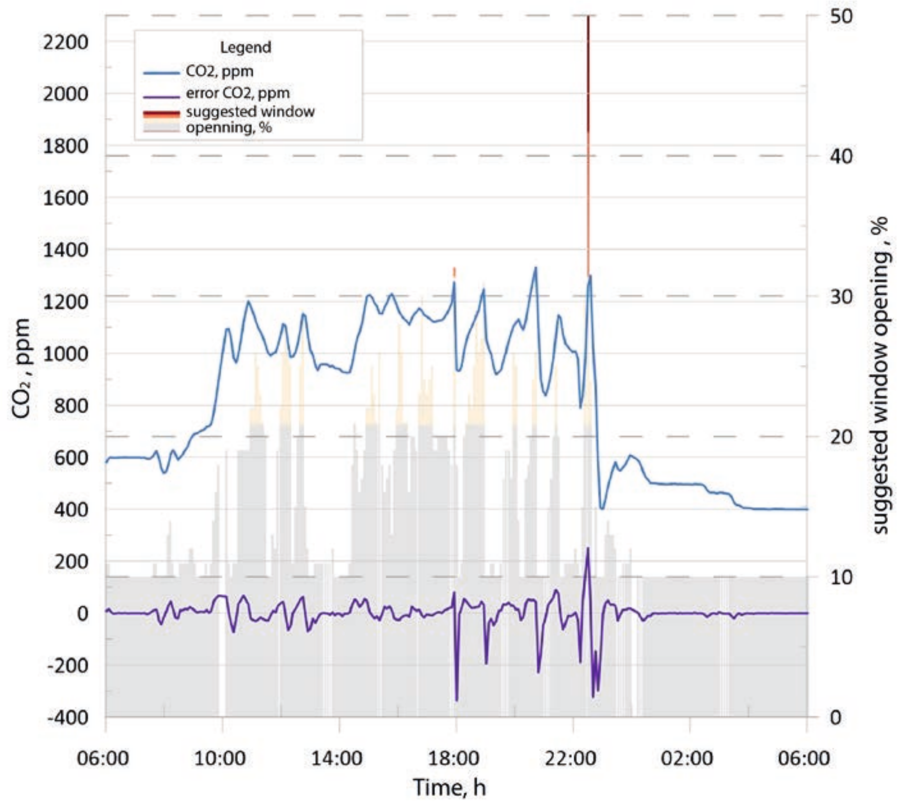

Fig. 13. Device test – change in concentration, CO_2 deviation and suggested window opening in 24 hours, adjustable window (author's work)

membership functions. In addition, following the recommendations of the device required frequent opening and closing of the window, which in many cases may be unfeasible or inconvenient for users of various types of rooms.

12. Conclusions

In many studies, it has been proven that air quality affects health, well-being and human performance. Since people spend most of their life in enclosed spaces, indoor air quality should be controlled in such a way that ensures its proper level. In many cases, buildings have not been equipped with a sufficiently efficient ventilation system to ensure adequate indoor air quality. The aim of this work was to create an innovative and economical solution supporting the natural ventilation system, without the need to modernise it.

The solution to the problem of low air quality in rooms with natural ventilation requires improvement of the system, which allows the ventilation air stream to be increased. Possible solutions include the installation of an air-quality monitoring device in the room with feedback for users. The solution was presented and tested in a study conducted in a Danish primary school by researchers (Wargocki, Da Silva, 2015). The prototype of the device presented in the work is an extension of the solution used during the aforementioned research.

The work presents a proprietary electronic device as a proposal to solve the problem of indoor air quality in rooms with natural ventilation. The device, based on the measured air parameters, indicates the optimal degree of window opening in the room, which should ensure adequate indoor air quality. In addition, the device informs the user about the need to close windows in the event of increased concentrations of pollutants in the outdoor air. The device uses the popular Raspberry Pi SBC, sensors measuring air parameters and other electronic modules. The device uses fuzzy control algorithms to calculate the appropriate degree of opening the window depending on the measurements of the air parameters. The prototype of the device displays the air parameters and the recommended extent of opening the windows on the device display. In addition, data is sent to the ThingSpeak server database, enabling the tracking of the device operation in real time through a mobile application.

The conducted test confirmed the effectiveness of the proposed solution for improving the indoor air quality in the rooms. The user's compliance with the time and manner of adjusting the window enabled increasing the efficiency of ventilation in the room. The average maximum CO_2 concentration in the indoor air was maintained at 1,200 ppm, a result of around 900 ppm lower compared to the concentration level obtained when the device was not used and the windows remained closed.

The device requires re-verification of the membership function and the way of calculating the conclusions in fuzzy control in order to increase the efficiency of operation, which would allow maintaining the CO_2 concentration level below 1,000 ppm. In addition, the device requires a reduction in the frequency of changes to proposed suggestions for opening the window. The authors of the work plan to introduce several improvements to the device in the future, among other strategies, enabling on the device to function with battery power, extending the possibility of communicating with other devices (e.g. an air purifier) and using machine learning methods to create a predictive model.

The presented device that helps to improve air quality in rooms with natural ventilation may in the future be an alternative solution to the methods used so far.

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Poprawa jakości powietrza wewnętrznego przy wentylacji naturalnej z wykorzystaniem kontrolera z logiką rozmytą

Streszczenie

Głównym celem badań było zaprojektowanie i walidacja urządzenia wspomagającego proces naturalnej wentylacji w pomieszczeniach. Do pomiarów fizycznych parametrów powietrza wykorzystano miernik CO_2 oraz termohigrometr. Urządzenie wykonano z wykorzystaniem minikomputera Raspberry Pi oraz sensorów optycznych. Prototyp obudowy wykonano w technologii druku 3D. Oprogramowanie urządzenia stworzono w języku programistycznym Python 2.7. W głównym algorytmie sterowania wykorzystano logikę rozmytą. Uzyskano poprawę jakości powietrza w przypadku jego zastosowania w pomieszczeniu z wentylacją naturalną. Opracowane urządzenie może stanowić rozwiązanie wspomagające system wentylacji w celu poprawy jakości powietrza.

Słowa kluczowe: logika rozmyta, jakość powietrza wewnętrznego, wentylacja naturalna